The History of Astrophysics in Antarctica

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Abstract
We examine the historical development of astrophysical science in Antarctica from the early 20th century until today. We find three temporally overlapping eras, each having a rather distinct beginning. These are the astrogeological era of meteorite discovery, the high energy era of particle detectors, and the photon astronomy era of microwave, sub–mm and infrared telescopes, sidelined by a few niche experiments at optical wavelengths. The favourable atmospheric and geophysical conditions are briefly examined, followed by an account of the major experiments and a summary of their results.

Keywords: history and philosophy of astronomy – site testing – cosmic microwave background – infrared: general – sub–millimetre – cosmic rays

1 Prehistory

The first written account of astronomical observations south of the Antarctic Circle dates back to 1772 (Bayly & Cook 1782), when the appointed astronomer and navy officer William Bayly made astrometric measurements aboard the ships "Discovery" and "Resolution". On their voyage, led by Captain James Cook, they circumnavigated Antarctica, crossing the Antarctic Circle three times from 1772 to 1775. The main objective of the observations was to establish positional accuracy in order to create charts of their discoveries. For that purpose they were equipped with several different compass designs, an astronomical quadrant and a Hadley sextant, as well as accurate chronometers built on the principles of Harrison's ship chronometer (Andrewes 1996). For stellar and lunar observations, a Dollond achromatic refractor and a Bird reflector were used. During the three year long voyage, two lunar eclipses were observed and many astrometric measurements were made. Their purpose, however, was not to advance astronomical science but to improve astronomical navigation.

Historical sources are not conclusive on who first sighted the continent of Antarctica. Among the credible candidates are the Dutch who sailed the southern sea under Dirck Gerritz (1544–1608). They also discovered Tierra del Fuego to be an island and claimed sighting Antarctica in 1599 as described by Isaac Lemaire in 1622 in the publication "Spieghel der Australische Navigatie" (Mirror of the Australian Navigation). Other candidates appeared much later (in the 1820's) and include the Russian Thaddeus von Bellinghausen, who saw the Finibul Ice Shelf and by "agreement" is credited with the first sighting just a few days before the young American sealer Nathaniel Palmer and the Briton Edward Bransfield, who sighted Trinity Land (Gurney 1998). Although numerous expeditions were carried out in the 19th century, it appears that none of them made any science-related astronomical observations. The reason for this omission is that the scientific disciplines that make Antarctica attractive as an observational platform today were simply non-existent or not advanced enough at the time. Additionally, astronomical equipment that remains functional under the adverse conditions would not easily have been manufactured and transported to Antarctica. It is therefore not surprising that the first, and literally hands-on, astronomical discovery in Antarctica was made in the unlikely

field of astrogeology.

2 The Early Days

Sir Douglas Mawson was the leader of the Australasian Antarctic Expedition, which lasted from 1911 until 1914. Its objective was to investigate the stretch of Antarctic coast between the then known boundaries in the west of Terra Nova, which was mapped by Scott's British Antarctic Expedition in 1910, and Gauss to the east, which was charted by the German Antarctic Expedition in 1902 (Mawson 1915). A base camp had been set up at Cape Denison in Commonwealth Bay, Adelie Land. It included a transit telescope and hut, whose purpose was for determining the longitude of Cape Denison through measurement of the transit times of stars across the local meridian. However no astronomy appears to have been done with the telescope.

From the base camp, field trips spanning several weeks and extending significant distances were executed by teams of three. On one of these excursions, Frank Bickerton led a sledging party with Leslie Whetter and Alfred Hodgeman. On the third day of the expedition, 18 miles from base and at about 3 000 ft elevation, they found a black object partially buried in the snow (see Figure 1). This chance find, discovered at 12:35 on 5 December 1912, turned out to be a stony meteorite, about five inches by three inches across (Bayly & Stillwell 1923). It was the first meteorite to be discovered in Antarctica, and the first astronomical observation of significance on the new continent[1]. Bickerton's diary entry for the day gives a detailed description of the appearance of the meteorite, and makes it clear that they immediately recognised it for what it was: "...meteorite ...covered with a black scale, internally of a crystalline structure, most of its surface rounded except in one place which looks like a fracture, iron is evidently present in it"[2].

It had been speculated since the Amundsen and Scott expeditions to the South Pole in 1911 that the dry and high altitude climate on the Antarctic plateau might be of advantage to astronomical observations. The US Navy Rear Admiral R. E. Peary, who had led the first successful expedition to the North Pole in 1909, was aware of this and in his relentless quest for discovery addressed his ideas in a letter to the director of Yerkes Observatory, Professor E. B. Frost (Peary & Frost 1912), suggesting that continuous observations during the course of a year could yield valuable results. He even went on to estimate the weight limit of the largest equipment part he would consider transportable, as well as the special construction measures required on site to enable instruments to be set up on solid ice. In 1897 the Yerkes Observatory built a 40 inch refractor telescope, the worlds largest refractor telescope ever built; it can be imagined that Peary sought to contact the Yerkes Observatory thinking they may have the research capabilities and interest to pursue astronomy in Antarctica. Frost, however, did not appear to be very enthusiastic about this idea. His response to Peary's suggestions was sent a mere three weeks later and clearly stated that the kind of observations that could be made from South Pole, and which he deemed useful, would not be possible for the lack of (mainly) precise timing instruments and he seemed generally reluctant to agree on the pursuit of an observatory at the South Pole[3].

Almost half a century later, the next significant astronomical discovery was made by Russian geologists operating out of the Lazarev Station (called Novolazarevskaya today), with a number of meteorites found and collected from the Lazarev region in 1961 (Tolstikov 1961; Ravick & Revnov 1965). The astrogeological importance of Antarctica, however, did not become evident until 1969,

[1] In an interesting footnote to the story, the Western Sledging Party also made the first attempt to use aero-transport in Antarctica with an air tractor – a light plane on skis (see Figure 2), with its main wings removed. It seized up on the second day, with several of its pistons breaking and smashing the propeller in the process. The trials of mechanising equipment are one of the great challenges facing Antarctic scientists, in particular automating experiments for operation at remote sites, unattended during winter months, as exemplified nearly a century later with the Automated Astrophysical Site Testing Observatory (the AASTO) – see §5.

[2] Quotation supplied by Frank Bickerton's biographer, Stephen Haddelsey. Bickerton's diary is held by the Scott Polar Research Institute in Cambridge, UK.

[3] There is an interesting footnote to this story. When the United States established the Center for Astrophysical Research in Antarctica (CARA), nearly 80 years later, the then director of Yerkes Observatory, Professor Doyal Harper, became the first director of CARA.

after a Japanese group of geologists established the first formal meteorite search programmes based on geological and glaciological evidence. They successfully retrieved many different kinds of meteorites including enstatite chondrites, hypersthene achondrites, type III carbonaceous chondrites and bronzite chondrite in the Yamato region (Nagata 1975). It was improbable that this accumulation of different meteorite types in the same location happened by chance, thus driving the development of theories explaining how meteorites falling in Antarctica could be transported by the moving ice sheets so as to be accumulated in a few particular locations — ablation zones in blue ice fields — where they could be easily found (Yoshida et al. 1971; Shima & Shima 1973).

3 Antarctica as an Observatory Platform

3.1 Cosmic Rays and Mawson Station

Modern astrophysics was not practiced in Antarctica until the 1950s. Previous astronomical observations undertaken were in a geophysical context, such as Earth magnetic field observations and auroral measurements. The first astronomical research programme was conducted by Australian scientists and developed from cosmic ray experiments carried out by the Physics department of the University of Melbourne, initiated by Professor Leslie Martin (Law 2000). In 1947, ANARE (Australian National Antarctic Research Expeditions) was established. Martin requested that three of his group's experiments be included in the first ANARE expedition, two to go to the sub-Antarctic Heard and Macquarie Islands (politically these are in Australia, not Antarctica, being part of the states of Western Australia and Tasmania, respectively), and the third to voyage to Antarctica on the expedition ship Wyatt Earp. In 1947 and 1948 stations were constructed on Heard and Macquarie Islands and ion chambers installed there. The Wyatt Earp continued to Antarctica and measurements were made using the third ion chamber by Philip Law, sometimes in the most difficult of circumstances given the frequent storms of the Southern Ocean. While not actually taking place on the continent, this was the first experiment explicitly designed for astrophysical purposes to be conducted in Antarctica.

In 1949 the cosmic ray equipment was returned from Heard and Macquarie Island for overhaul, but in 1950 Martin decided to end cosmic ray research in Melbourne. The programme moved to the University of Tasmania, under the direction of Geoff Fenton. Mawson Station, Australia's first Antarctic station, was established in 1954 and a cosmic ray observatory built in 1955. That same year Nod Parsons, a member of Fenton's group, travelled to Mawson on the Kista Dan and installed Geiger counters (Parsons 1957). Three tonnes of lead absorber were required and packed into 120 boxes on the tiny 1 200 tonne vessel! These were the first astrophysical experiments to actually take place on the continent, and the heralded the start of the Mawson cosmic ray programme which still continues today.

3.2 The International Geophysical Year

In 1952, following a suggestion by the US National Academy of Science member Lloyd Berkner, the International Council of Scientific Unions (ICSU) proposed to execute a comprehensive series of global geophysical activities to span the period from July 1957 to December 1958. This was to be called the "International Geophysical Year" (Opdishaw 1957), and it was modelled after the International Polar Years of 1882–1883 and 1932–1933. The intention was to allow scientists from all over the world to take part in a series of coordinated observations of various geophysical phenomena. Initially, 46 member states participated and 67 countries had become involved by the end. In view of the high geomagnetic latitude, the United States proposed a cosmic ray detector be located at McMurdo Station. The US National Science Foundation asked Dr. Martin A. Pomerantz, a leading cosmic ray physicist at the time, whether he was interested in setting up such a device in Antarctica (Pomerantz 2000). He accepted and brought with him the great experience collected while working on high altitude balloon experiments in the late 1940s.

A second cosmic ray detector was installed at the South Pole in 1964, which also provided an opportunity to evaluate the Pole for other kinds of astronomical observations. During operations in

1964, a semi-quantitative analysis of stellar and solar observation conditions were made using a small 3.5 inch aperture telescope. A report issued in 1970 by the US National Academy of Science and written by Arne A. Wyller, who was at the time Professor at the Bartol Research Foundation, concluded that the seeing would offer excellent conditions for optical astronomy at the Pole, and suggested the Pole should be considered further as an astronomical site. Estimates of the precipitable water vapour content in the air above the South Pole also indicated that conditions were very favourable for infrared and millimetre-wave observations (Mullan, Pomerantz & Stanev 1989). Nevertheless, no larger effort was started to take advantage of these conditions for another decade.

3.3 The South Pole

In 1979 the first optical research programme was performed at South Pole. Eric Fossat and Gerard Grec (both of the Observatoire de Nice), and Martin Pomerantz coupled a sodium vapour cell to a small telescope and obtained an unbroken run of over 120 hours of observations measuring solar oscillations. These data allowed about 80 harmonics of solar eigenmodes to be discovered (Grec, Fossat & Pomerantz 1980, 1983; Fossat et al. 1987), with periods ranging from about 3 to 8 minutes. In the 1981–82 summer an array detector was added to provide increased angular resolution for the solar observations, allowing features as small as ten seconds of arc to be resolved (Pomerantz, Wyller & Kusoffsky 1981; Pomerantz, Harvey & Duvall 1982; Harvey 1989). The latitude-dependent measurement of the various eigenmodes of solar oscillation provided evidence that the structure of the convection zone inside the Sun is different near the equator than it is at higher latitudes.

In the 1980s, the first projects were envisaged with an initial goal of observing the galactic infrared emission. Measurements of water vapour content in the atmosphere made with a site-testing meter in the summer of 1974 (Westphal 1974) had shown that it was lower than at Mauna Kea, the world's premier infrared observatory. The first experiment to attempt to take advantage of this characteristic was a US–France collaboration that took place in 1984–85 (Pomerantz 1986), involving Richard Gispert, Jean-Michel Lemarre, Francois Pajot and Jean Loup Pajot working with Pomerantz. They used a 45 cm sub-millimetre telescope named EMILIE (Emission Millimetrique), which had been designed to work on the 3.6 m Canada-France-Hawaii Telescope on Mauna Kea, Hawaii. It was by far the most ambitious and logistically difficult astronomical programme then undertaken in Antarctica, requiring the transport of liquid helium to Antarctica all the way from the USA. The telescope was scanned across the Galactic plane with a $0.5°$ beam, detecting the emission from the Galactic centre at 900μm (Pajot et al. 1989), and measuring the dust emission at four wavelengths (460, 720, 850 & 920μm) in several star-forming complexes in the southern Galactic plane, so allowing the temperature and infrared luminosities of these regions to be estimated. Using an upgraded version of EMILIE an attempt was made in 1986–87, by Mark Dragovan, Tony Stark and Robert Wilson of the ATT/Bell Laboratories, to measure the cosmic microwave background anisotropy. This was to be the first in what was to become an increasingly sophisticated series of experiments which produced, a decade later, a series of landmark results concerning the angular scales and frequency of the anisotropy (see §7.4).

In 1988, the US National Science Foundation awarded a grant for the South Pole Astrophysics Research Center which resulted in a conference held at the University of Delaware in 1989. The conference proceedings were published (Mullan et al. 1989) and ultimately led to the formation of CARA, the Center for Astrophysical Research in Antarctica, in 1991 (Harper 1994). CARA consisted of a consortium of US universities, and was run from Yerkes Observatory in Wisconsin (part of the University of Chicago) under director Doyal Harper.

A year round observatory at the South Pole was established by CARA, with telescopes planned to operate in the infrared, sub-millimetre and microwave bands. A special "Dark Sector", where anthropogenic interference was to be kept minimal, was set aside 1 km away from the Pole for the astronomical experiments. These have been centred around the MAPO Building (Martin A Pomerantz Observatory; see Figure 3), named in honour of Pomerantz's many pioneering contributions to the development of astrophysics in Antarctica. In addition to supporting several telescopes, MAPO also contains a fully-equipped workshop, which has proved to be invaluable in maintaining the observatory.

A programme was also begun to evaluate the transparency, darkness, water vapour content and stability of the Antarctic sky from infrared to millimetre wavelengths, for comparison to astronomical sites at temperate latitudes.

3.4 Developments within Australia

The formation of CARA sparked interest in Antarctic astronomy by other countries, particularly Australia. Martin Pomerantz first stimulated discussion by addressing a meeting of the Astronomical Society of Australia in Hobart in 1986 about the activities then being conducted at the South Pole (Pomerantz 1986). This led to Peter Gillingham of the Anglo Australian Observatory making a presentation in June 1989 to a meeting at the Academy of Sciences in Canberra, convened to discuss future plans for astronomy in Australia, on the opportunity offered by Antarctica. The desirability of joining the establishment of an international observatory in Antarctica, possibly at the highest point of the plateau (Dome A), was then publicly discussed at the July 1990 International Astronomical Union Asia–Pacific Regional Meeting held at the University of New South Wales in Sydney (Gillingham 1991). Following a government-sponsored visit to Australia by French scientists in April 1991, collaboration in Antarctic astronomy was viewed as a high priority. A return visit to France the following year established links with the Université de Nice group and the idea born to measure micro-thermal turbulence in order to quantify the seeing. Gillingham and Jean Vernin (of the Université de Nice) then visited CARA in Wisconsin to advance plans for making micro-thermal measurements. A visit to John Bally of the University of Colorado by Michael Burton in September 1992 further established links with CARA, and a collaboration was formed to measure the infrared sky brightness using a recently superseded infrared photometer of the Anglo Australian Observatory (the IRPS – see §5). Jamie Lloyd, who was at the time completing his undergraduate degree at the University of New South Wales, and Michael Burton took these two experiments to the South Pole in January 1994, the experiments having largely been put together by then graduate student Rodney Marks and his supervisor Michael Ashley at UNSW. By the end of that year, the Joint Australian Centre for Astrophysical Research in Antarctica (JACARA) was established between the University of New South Wales in Sydney and the Australian National University in Canberra to facilitate further cooperation with CARA (Burton et al. 1996).

3.5 International Developments

At the 21st General Assembly of the International Astronomical Union (IAU), held in Buenos Aires in 1991, a working group chaired by Peter Gillingham was established to encourage the development of Antarctic astronomy. Seventeen papers were presented at the meeting (see Gillingham 1992) and a resolution encouraging international collaboration in Antarctic astronomy was drafted and adopted by the General Assembly. At the 1994 IAU General Assembly in the Hague, a full-day session was held on the topic, with the chair of the working group passing to Michael Burton. A couple of weeks later in Rome a special session on Antarctic Astronomy was held at the 22nd SCAR meeting (Scientific Committee for Antarctic Research). This meeting was organised under the auspices of STAR, the Solar Terrestrial and Astrophysical Research working group of SCAR, with John Storey (also of the University of New South Wales) becoming the vice-chair with responsibilities for astrophysics within STAR. SCAR also passed a resolution recognising the scientific value of Antarctic astronomy and calling for the development of the field. Antarctic astronomy meetings have been regular features of IAU and SCAR meetings ever since. STAR has since been re-organised as the Standing Scientific Group on Physical Sciences (SSG/PS), with both an expert group (AAA – Antarctic Astronomy & Astrophysics) and an action group (PASTA – Plateau Astronomy Site Testing in Antarctica), providing it with input.

4 The Advantages of the Antarctic Plateau for Astronomy

At the South Pole, with its relatively high altitude of 2 835 m above sea level and an equivalent pressure altitude of 3 200 m due to the extreme cold, the transparency of several atmospheric windows is greatly improved. This is largely due to the extremely low levels of precipitable water vapour in the atmospheric column, which regularly falls to below 250 μm ppt H_2O, compared to levels of $\sim$1 mm at the best mid-latitude sites (Townes & Melnick 1990).

The advantages of the Antarctic plateau for astronomy at infrared wavelengths also stem from its extremely cold temperatures, stable atmosphere, and the ability to observe objects continuously throughout the long winter night (Harper 1989; Storey & Hyland 1993; Burton et al. 1994; Burton 1996; Ashley 1998; Storey 2000). The sky at the South Pole at thermal infrared wavelengths is darker than at any mid-latitude site by between one and two orders of magnitude, and thus dramatically reduces the background noise and minimises the sky fluctuations (Harper 1989; Burton, Allen & McGregor 1993; Nguyen et al. 1996; Ashley et al. 1996; Phillips et al. 1999; Chamberlain et al. 2000).

In 1991 Peter Gillingham suggested that high sites on the Antarctic plateau might also provide unprecedented seeing ("super-seeing"), based on the absence of diurnal temperature cycles in winter and the slow settling of air from the stratosphere over the plateau (Gillingham 1993a, 1993b). This would occur above a shallow surface inversion layer, where the air at the ice surface is cooler than at the top of the inversion layer by up to $\sim 20°$C, typically only 200–300 m higher. Turbulent mixing in this surface inversion layer has been confirmed as causing the relatively poor surface seeing ($\sim$1.5" in the visual) at the Pole. However, because there is little thermal inhomogeneity (other than in the air near the telescope) and because the air moves relatively slowly, the isoplanatic angle and coherence time are both greatly increased over their values at temperate-latitude sites. This provides conditions which are very favourable for adaptive correction of wavefronts (Mark 2002). Since there is no jet stream contributing to high-altitude turbulence at the Pole, the seeing is dominated by the contribution from this narrow surface layer. Not only has this significance for attempts to recover the diffraction limit from the turbulence induced seeing, but also for conducting astrometric interferometry, reducing the phase errors due to the proximity of the turbulence cells to the telescope, compared with the high altitude turbulence encountered at mid-latitude observatories (Lloyd, Oppenheimer & Graham 2002). On the summits of the Antarctic plateau, where wind speeds are at their lowest (as this is where katabatic winds originate), even the surface seeing contribution is expected to be very small at times. Experiments are now being conducted at the high plateau site of Dome C to quantify this attribute (Travouillon et al. 2003c).

In the cosmic ray spectrum the Earth's magnetic field normally shields (or at least deflects) a significant amount of the heavier charged particles travelling through space. At the magnetic Poles the magnetic field lines enter the surface of the Earth almost vertically, thus creating a port of entry for charged particles. Thus Antarctica is a particularly suitable place to study cosmic rays.

Another significant advantage in Antarctica is found in the vast amount of transparent ice over the plateau, reaching to a depth of 3–4 km below the surface. This can be used to create a neutrino particle detector of enormous volume, which is needed in order to be able to record the minuscule number of neutrinos that do in fact interact with nuclei in the ice, or underlying rock, as they pass through the Earth.

5 Site Testing at the South Pole

The first testing to measure the near-IR sky brightness from 2–5μm was conducted from 1994–1996 using the Infrared Photometer Spectrometer or IRPS (Ashley et al. 1996; Phillips et al. 1999), originally used as the Anglo-Australian Telescope's front-line IR instrument in the early 1980s[4]. At the same time, the 60 cm SPIREX telescope was also used to measure the sky brightness from 1–2.5μm. From 2.3–5μm the sky was found to be between 10 and 100 times darker than at temperate latitude

[4]When it was used, among other things, to discover a cluster of hot young stars in the centre of the Galaxy (Allen, Hyland & Jones, 1983), and to find windows in the infrared bands which could be used to peer through the atmosphere of Venus to see the tops of the highest mountains (Allen & Crawford 1984).

sites. Microthermal turbulence measurements were also conducted from a 30 m high tower (in 1994) and from balloons (in 1995) to characterise the contribution of the boundary layer to atmospheric seeing (Marks et al. 1996, 1999).

In order to better provide site characteristics and to facilitate further site evaluation, the Automated Astrophysical Site Testing Observatory (AASTO; see Figure 4) was established at the South Pole in 1997 (Storey et al. 1996). This self-powered, autonomous laboratory, hosting a suite of site testing instruments, was developed as a practical solution to the challenge of obtaining data in a harsh remote environment with limited electrical power and with no human intervention. Experiments were designed and built for the AASTO to measure the electromagnetic spectrum from the UV to the sub-millimetre in order to quantitatively assess the site for astronomical use. The AASTO project began a collaboration between the University of New South Wales and the Australian National University, in conjunction with CARA, and led to the formation of JACARA (Burton et al. 1996). It continued to operate at the South Pole until the end of 2003, when it became the platform for conducting an experiment to search for extrasolar planetary transits (SPETS – the South Pole Exoplanet Transit Search; Caldwell et al. 2003).

The AASTO programme had to overcome considerable technical challenges, not the least being the difficulty of obtaining a reliable power supply able to operate without interruption or maintenance over the winter months. The thermo-electric generator (or TEG) used to provide power is driven via a catalytic oxidisation of propane fuel. This catastrophically failed several times during the first three years of operation, leaking freon which decomposed over the oxidiser, producing hydrochloric and hydrofluoric acid. The net result was considerable chemical erosion of the instrument suite (Storey, Ashley & Burton 2000). Without some considerable efforts by the UNSW team over the summer months, plus a series of heroic efforts by successive winter-over scientists (Paul Sullivan, Michael Masterman and Charlie Kaminski), the AASTO programme would not have succeeded, and likely the whole site testing programme would have been put back several years. In January 2003, an improved version of the laboratory was transported to, and deployed, at Dome C – the AASTINO (Antarctic Astrophysical Site Testing International Observatory; Lawrence et al. 2003), where it provided the first wintering facility at the new Concordia Station, currently under construction by the French and Italian national Antarctic programmes.

The AASTO package consisted of a suite of instruments, developed from 1997–2001, including the Near-Infrared Sky Monitor (NISM) and the Mid-Infrared Sky Monitor (MISM) (Storey et al. 1999), which were both used to measure sky brightness in the respective wavebands (Lawrence et al. 2002; Chamberlain et al. 2000); the Antarctic Fibre-Optic Spectrometer (AFOS), used to measure atmospheric transmission from the UV to the far-red (240–800 nm; Boccas et al. 1998, Dempsey et al. 2003b); a Sonic Radar (SODAR), used to measure the level of turbulence in the surface inversion layer (Travouillon et al. 2003a); the Antarctic Differential Image Motion Monitor (ADIMM), used to determine the astronomical seeing by measurements of stars (Travouillon et al. 2003b); and the Sub-millimetre Tipper (SUMMIT), used to measure the 350 μm sky brightness (Calisse et al. 2004).

In addition to the astronomical site testing data, the AASTO also collected weather data such as temperature, wind speed, wind direction and atmospheric pressure. The AASTO instruments measured the sky brightness from 1.25–14 μm and recorded the incidence of clear skies suitable for astronomical observations. Around 50% of all 'nights' at the Pole were found to be of excellent quality. In the near-infrared, the lowest background levels were measured in a window between 2.3 μm and 2.45 μm, where it attained levels of less than 70 μJy/arcsec^2, values comparable to measurements made from high altitude balloons and two orders of magnitude less than at mid-latitude sites. Residual emission in this window is thought to come from airglow at altitudes above 38 km and, interestingly, no correlation was observed between the sky brightness and auroral activity. At longer wavelengths (from 3–30 μm), while the background reduction was found to be only one order of magnitude, the advantages of Antarctica were found to be especially significant. In these bands infrared arrays rapidly saturate due to the high thermal backgrounds, atmospheric windows are only partially transparent, and sky fluctuation noise is high, limiting the stability of measurements. All these attributes were found to be improved at the Pole. For wavelengths shorter than 2.3 μm, however, the gains are fairly modest because the sky brightness is dominated by OH airglow rather than thermal emission, and

this varies little around the world. Since the quality of the observing conditions at wavelengths longer than 3 μm depends principally on temperature, it did not come as a surprise that good observing conditions were found to extend well beyond the boundaries of the polar night.

6 High Energy Physics

6.1 Mawson Station

As described in §3.1, in 1955, two muon telescopes were built and shipped to Mawson Station on the Antarctic coast and installed by Nod Parsons (Parsons 2000). The design for each telescope was based on three trays of Geiger counters, each 1 m^2 in size, placed inside a specially constructed building – the cosmic ray hut. The relative ease of operation made them suitable for the first experiments to be located in Antarctica and cosmic ray detectors are now installed at many Antarctic research stations. These first telescopes still required a significant amount of maintenance, however, and a faulty paper recorder meant that measurements of the great solar flare event of 23 February 1956 were compromised. In December 1956, a 12-counter neutron monitor was sent to Mawson to be a part of the Australian Neutron Monitor Network (McCracken 2000). It has been a great contributor to measurements of many solar flare events since 1957, most notably the event of 4 May 1960, where it provided experimental verification of the spiral nature of the Solar System magnetic field long before direct measurements of the field by satellites (McCracken 1962). The monitors have also had a crucial role to play in the calibration of space-based measurements.

In 1968, observations commenced at Mawson with two high zenith angle muon telescopes, pointing north and south at 76° (Jacklyn 2000). One significant result was finding a latitude-dependent sidereal semi-diurnal variation (Jacklyn & Cooke 1971). A new cosmic ray observatory was constructed in 1971, designed largely by Attila Vrana who was an electronics engineer with the Australian Antarctic Division (AAD). A vertical shaft was driven through the granite rock to a depth of 40 mwe (metres of water equivalent) to filter out the lower energy particles. Two vaults were constructed at the bottom, one of which would harbour an underground muon telescope. On top of this was the building containing the high zenith angle telescopes and the neutron telescope. The detectors used, however, remained as Geiger counters until their replacement in 1982 by proportional counters. These telescopes found an intriguing solar modulation at the time of a very large cosmic ray decrease in July 1982 (Jacklyn, Duldig & Pomerantz 1987). These variations became known as isotropic intensity waves, but since there have been no clear recurrences of the original phenomenon they remain something of a mystery. Further upgrading continued during the 1980's, under the direction of Marc Duldig, to fully automate the system and transfer the data by satellite back to the AAD headquarters in Hobart, Tasmania. To date, the muon detector at Mawson remains the only such southern hemisphere telescope at Polar latitudes, along with one in Tasmania (Duldig 2002). A full historical account of the Australian cosmic ray programme can also be found in this paper.

6.2 South Pole

The GASP telescope (Gamma Astronomy at the South Pole; Morse & Gaidos 1989) was installed at the Pole from 1994-97 by the University of Wisconsin-Madison. Six metre-sized mirrors were used to look for the Cherenkov light from cosmic rays which are generated by gamma ray interactions in the upper atmosphere. The long, dark night, combined with the constant zenith angle that an astronomical source would have, were the primary reasons for installing the telescope at the Pole, following the building of a similar facility at Haleakala Observatory in Hawaii. However, the facility was not successful with its objective of finding celestial sources of gamma rays, as no clear detections of discrete sources were ever made.

Cosmic rays with energies of $\sim 10^{14}$ eV are measured by large collecting area air shower arrays. At these high energies the flux of events is too low to measure with short duration balloon flights, and the collecting area too small for expensive satellite experiments. The constant zenith angle of any astronomical sources at the South Pole greatly simplifies the analysis of the air shower data, and

large collecting area experiments can readily be built there. Two such instruments have been built at the South Pole Station to measure cosmic rays – SPASE and SPASE–2.

SPASE, the South Pole Air Shower Array, was built just 200 m away from the South Pole and near to the Geodesic Dome. It was established in 1987 and ran continuously for 10 years. SPASE was built under the direction of Alan Watson (University of Leeds) and Martin A. Pomerantz (the same Pomerantz who built the first cosmic ray detectors at McMurdo in 1961)[5] and was a joint effort between the Bartol Research Institute of the University of Delaware and the cosmic ray group of the University of Leeds (Smith et al. 1989). Sixteen scintillation detectors were spread over a collecting area of 6 200 m^2. The experiment specifically aimed to find cosmic sources of gamma ray emission. The trajectories of these photons are not altered by the galactic magnetic field, unlike the case for charged cosmic ray particles. However no such sources were ever found (van Stekelenborg et al. 1993), and the particle events detected had an isotropic distribution across the sky.

Construction started in 1994 on an enhanced array called SPASE–2 (Dickinson et al. 2000) in the "Dark Sector" of South Pole Station. SPASE–2 was built on top of the Antarctic Muon And Neutrino Detector Array (AMANDA, see below), which was simultaneously also under construction. The new air shower facility began operation in 1996, with a larger array than SPASE, containing 120 scintillator modules spread over an area of roughly 16 000 m^2. An additional 9 air-Cherenkov telescopes were placed around them, a separate experiment given the name of VULCAN. SPASE–2 is sensitive to cosmic rays with primary energies from 10^{14} to 3×10^{16} eV. It was also built with the express purpose of working in concurrence with the AMANDA neutrino detector to measure the electron component of air showers while AMANDA measured their muon component.

The AMANDA project has become the largest single scientific programme at the South Pole, with collaborating scientists from 20 institutions in the USA, Sweden, Germany, Belgium, the UK and Venezuela (Andres et al. 2000). AMANDA contains widely spaced photomultiplier tubes (PMTs; see Figure 5), connected together by strings and placed into water-filled holes drilled into the ice. The holes range from several hundred metres to 3 km in depth and the water in them rapidly re-freezes, trapping the PMTs within the ice. High energy neutrinos coming up through the Earth will *very* occasionally interact with nuclei in the ice or rock and so create a muon, which in turn emits Cherenkov radiation when passing through the ice. By measuring the arrival times of the light pulses at the PMTs, the origin of the neutrinos and their arrival rate can be determined. In addition, they may possibly be brought into coherence with events measured by SPASE. The detectors in AMANDA point downwards, to look for neutrinos that enter the Earth in the northern hemisphere and pass right through it, before encountering a nucleus in the ice. They point down in order to shield the detector from the vastly greater count rate generated by downward passing cosmic rays. The first four strings of PMTs were deployed over the 1993/94 summer period (AMANDA–A), but at the 800–1 000 m depth they were placed at, the ice was found to contain too many air bubbles to allow the muon tracks to be followed. Since then the array has been expanded twice, with 19 strings placed at depths from 1 500–2 000 m (AMANDA–II), and containing 677 optical modules. The great transparency of the ice at these depths, where the absorption length reaches to ~ 100 m, and the absence of biological contaminants, makes the Antarctic ice particularly suitable for such an experiment. So far over 1 500 neutrino events have been detected, isotropically distributed over the northern sky (Andres et al. 2001, Wiebusch et al. 2002).

6.3 Neutrino Experiments Under Development

No individual sources of neutrino emission have yet been detected, however. Nevertheless, the sensitivity thresholds of AMANDA are much as expected, with about three atmospheric neutrinos detected per day. It is anticipated that the next generation neutrino telescope, IceCube, will be able to detect individual cosmic sources of neutrino emission, such as active galactic nuclei and gamma ray bursters, thus opening up a completely new field of observational astronomy (Halzen 2004). IceCube will use a cubic kilometre of ice as its collecting volume, opening up unexplored bands for astronomy including

[5] As an interesting footnote, he went on to own a Nissan and later a Ford car dealership near Huntsville, Alabama, for about ten years.

the PeV (10^{15} eV) energy region. At such high energies the Universe is opaque to γ-rays originating from beyond the edge of our own galaxy, whereas cosmic rays of this energy do not carry directional information because of their deflection by magnetic fields.

Two experiments aimed at detecting ultra high energy neutrinos (i.e. $> 10^{20}$ eV) through their interaction with nuclei in the Antarctic icecap are also under development. At such extreme energies the only particles capable of reaching the Earth from cosmological distances are neutrinos. Electrons, scattered into the particle cascade when the neutrinos interact with the ice, emit a pulse of Cherenkov radiation, peaking in the radio at frequencies of a few hundred MHz. A prototype experiment called the Radio Ice Cherenkov Experiment, or RICE, operated at the South Pole over the 1995/96 and 1996/97 summers (Allen et al. 1998) using two of the AMANDA bore holes. It is being developed further to work with the full AMANDA array. Another experiment under development is ANITA, the ANtarctic Impulsive Transient Antenna, scheduled to be deployed from a long duration balloon flying at 40 km altitude. Ice is transparent to radio waves of frequencies ~ 1 GHz, so that ANITA will be sensitive to neutrino-generated radio pulses occurring from a large part of the Antarctic ice sheet, equivalent to having an effective telescope collecting area of 1 million square kilometres (Barwick et al. 2003)! ANITA is planned to be launched from McMurdo in 2005.

7 Photon Astronomy

We divide photon astronomy into four bands, defined by four atmospheric windows that are open, for our purposes of describing the various astrophysical experiments undertaken in Antarctica. These are the optical, infrared, sub-millimetre and microwave windows.

7.1 Optical

Optical astronomy has mainly been employed for site testing and evaluation in Antarctica, with limited astronomical applications. The South Pole Optical Telescope (SPOT, a 2 inch periscope style telescope; see Figure 6) programme was operated by the University of Florida from 1984 to 1988 (Chen et al. 1987). Measurements were taken during the austral summer to evaluate the visual seeing conditions. Long period measurements were also made in winter, obtaining up to one week of continuous data of the light curves of variable stars, including the Wolf-Rayet star γ^2 Velorum. However, the data was affected by clouds, and the useful observing time did not exceed that of mid-latitude observatories (Taylor 1990).

Optical telescopes have also been used to measure the visual seeing at night at the Pole, through the use of DIMMs (differential image motion monitors; Bally et al. 1996; Dopita, Wood & Hovey 1996). These monitor light from a star through several adjacent apertures in order to measure the stability of the atmosphere. Two such experiments were the HDIMM on the SPIREX telescope (Loewenstein et al. 1998) and the ADIMM used with the AASTO (Travouillon et al. 2003b). The ice-level seeing at the Pole was found to be relatively poor, of order $1.5''$, but since it is nearly all produced in a narrow surface inversion layer, the prospects for adaptive optic correction are extremely promising (Marks 2002; see §4).

Argentinean astronomers examined site conditions at General Belgrano II Station, located at 79° S on the coast. They used a Celestron CG11 telescope and measured an average $3.8''$ viewing, which is not good enough for serious observations. The extinction across the optical bands was also found to be high. The U band, however, may potentially be interesting for observation of auroral activity and effects associated with the ozone hole (Mosconi et al. 1990).

7.2 Infrared

The South Pole Infrared Explorer (SPIREX; see Figure 7), was a 60 cm telescope observing from 1–5 μm at the South Pole. It operated with two different instruments – the GRism IMager (GRIM, from 1993 until 1997; Hereld 1994) and the Abu camera (in 1998 and 1999; Fowler et al. 1998). SPIREX was installed just in time to witness the collision of Comet Shoemaker-Levy 9 with Jupiter in July

1994, the only telescope in the world with the opportunity to continuously observe the week-long series of impacts. A total of 16 impacts were recorded (Severson 2000).

SPIREX's principle scientific work (see Rathborne & Burton (2004) for a fuller description) was for imaging PAHs (polycyclic aromatic hydrocarbons) at 3.3 μm, tracers of photodissociation regions (the surface of molecular clouds excited by far–UV radiation from young stars). PAHs were imaged in NGC 6334 (Burton et al. 2000) and in the Carina nebula (Brooks et al. 2000; Rathborne et al. 2002). Extensive shells of PAH emission were found, wrapped around embedded protostellar objects.

SPIREX also was used to measure infrared excesses at 3.5 μm from hot dust in disks around pre-main sequence stars. Infrared excesses from disks were searched for in the nearby low mass star forming clouds of Chamaeleon I (Kenyon & Gomez 2001) and η Chaemaeleontis (Lyo et al. 2003). At 3.5 μm the signature from disk emission was found to be much more readily detectable than in the normally used 2 μm band. Despite its modest size, the SPIREX telescope obtained the then deepest image at 3.5 μm from any telescope, achieving a detection threshold of 18.2 magnitudes per square arcsecond in a 10 hour observation of the 30 Doradus region of the Large Magellanic Cloud (Rathborne & Burton 2004).

7.3 Sub-millimetre

Heavy elements are created in nuclear processes in the interiors of stars and returned to the interstellar medium through winds and supernova. Carbon is the most abundant of these heavy elements, emitting at 370 μm and 610 μm in the submillimetre, and plays a significant role in many astrophysical processes. Atomic carbon observations are difficult from Earth because water vapour makes the atmosphere opaque to much of the sub-millimetre band. At the South Pole these windows are open and make it possible to observe neutral carbon as a matter of routine.

AST/RO, the Antarctic Sub-millimetre Telescope and Remote Observatory (see Figure 8), is a 1.7-metre telescope built for this purpose, with the primary aim of measuring the dominant cooling lines from dense interstellar gas, where stars are forming (Lane & Stark 1997; Stark et al. 2001). Observation of these lines allows the temperature and density of the gas to be determined. AST/RO has been in almost continuous operation since January 1995, making it the longest serving astronomical telescope on the Antarctic plateau to date. It is a general-purpose facility, used both for astronomy and aeronomy at wavelengths between 200–2000 μm, and has been equipped with several detector systems (and given an eclectic set of names – Major Dobbin, Wanda, FLaMR, PoleSTAR, TREND and SPIFI, as well as having a Fourier transform spectrometer for aeronomy studies; see Table 1). The optics are offset to produce high beam efficiency and to avoid inadvertent reflections and resonances. The primary reflector is made of carbon fibre with a surface accuracy of about 9 μm. It has Coudé and Nasmyth focii. Most of the spectroscopy performed has used heterodyne receivers mounted on an optical table in the warm coudé room. AST/RO operates continuously throughout the winter period. The science carried out has concentrated on measurement of emission lines of atomic carbon and carbon monoxide from photodissociation regions, in both the Milky Way and the Large Magellanic Cloud, which is well placed for observation from the South Pole. AST/RO also contributed to the South Pole site evaluation programme, by measuring characteristics of the sub-millimetre sky emission.

The major accomplishments of AST/RO to date include the first detection of [CI] emission in the Magellanic Clouds (Stark et al. 1997); a survey of [CI] and CO emission from the HII region/molecular cloud complexes of Carina (Zhang et al. 2001) and NGC 6334 (Yan et al. 2004); a survey of the [CI] emission from high galactic latitude molecular clouds (Ingalls et al. 2000) and from the inner few degrees of the Galaxy, to determine the CI/CO ratio as a function of metallicity, and to compare with the LMC/SMC and the solar neighbourhood (Ojha et al. 2001; Martin et al. 2004).

The all-year operation, as well as the high degree of automation, requiring only one winter-over astronomer to execute the observations, and the warm environment for the instruments, have all contributed to the success of AST/RO. It has been the most productive telescope built in Antarctica.

The Submillimetre Polarimeter for Antarctic Remote Observing (SPARO) was a 9-pixel 450 μm polarimetric imager developed by scientists at Northwestern University in Chicago for use with the Viper telescope, where it was installed from 2001–2003. SPARO has been used to determine the

direction of interstellar magnetic fields through the polarisation of dust emission in the sub–mm, for instance mapping the magnetic field through the inner several hundred parsecs of the Milky Way. As a result a large-scale toroidal magnetic field was detected over the region of the Galactic centre (Novak et al. 2003).

7.4 Microwave

The Cosmic Microwave Background Radiation (CMBR) spectrum resembles that of a blackbody at a temperature of 2.7 K. It carries a wealth of information about the origin and evolution of the Universe in its signal, allowing predictions of the standard Big Bang model to be rigourously tested. The angular power spectrum of the CMBR contains information on the structure that existed at decoupling (the time when radiation and matter separated). Anisotropy in the matter distribution at this time can also be detected in the CMBR as minuscule variations in the angular distribution from a smooth 2.7 K blackbody spectrum. The amplitude and spatial distribution of the anisotropy are directly related to the conditions in the early Universe which ultimately gave rise to the formation of structure, such as the super-clustering of galaxies. Due to the extreme stability of the atmospheric microwave emission, Antarctica has proved to be the pre-eminent Earth-based site for CMBR measurement, and has hosted a series of increasingly sophisticated experiments as a result.

In the late 1980s, a ground-based experiment was carried out by an Italian research team in Terra Nova Bay to measure anisotropies in the CMBR at an angular scale of 1.3°. A 1 m diameter flux collector with a He^3 cooled bolometric detector, sensitive to radiation with a wavelength between 1.86 and 2.34 mm, was used. Observations were carried out during the Antarctic summer period (dall'Oglio et al. 1988).

At about the same time the South Pole was also chosen as a site for several CMBR investigations. After some trial experiments the first major campaign was conducted during the 1988-89 summer. It took place in what was dubbed "Cucumber land" by the South Pole support staff in view of how the experiment appeared to them! They were set up in three Jamesway tents (hence the appearance of a "cucumber" – a long, cylindrical green tent) about 1 mile grid south east from the Geodesic Dome, and involved two research groups – from Princeton led by Jeff Peterson and from the University of California, Santa Barbara, led by Phil Lubin. Several experiments were involved. A one square metre Bell Labs offset horn antenna was used with a single-pixel 1 mm wavelength bolometer (called "Miss Piggy"), borrowed from the University of Chicago airborne astronomy programme. UC Santa Barbara provided a balloon gondola and Princeton trialled the "White Dish" experiment.

It took a few years before the CMBR experiments began obtaining results. The first significant result came using the White Dish (Tucker et al. 1993), from measurements taken between 1991 and 1993 which provided tight limits on the anisotropy at higher angular scales than had been probed with the COBE satellite (ie. $\Delta T < 63\mu$K for $\theta \sim 0.15°$). White Dish comprised of a 1.4 m telescope with a single-mode waveguide bolometer operating at 90 GHz. With the formation of CARA, CMBR observations at the Pole became incorporated into the COBRA programme (COsmic microwave Background Radiation Anisotropy). COBRA's first experiment was the Python telescope, built in 1992. This 0.75 m instrument used three detector systems to map the CMBR at 38, 42 and 90 GHz, respectively. The CMBR structure analysis provided some of the best confirmed data of the anisotropies on degree angular scales at the time (Coble et al. 1999). By including many repetitions and variations of the same measurement, Python showed that the results were reproducible and not instrumental in origin. To help discriminate between the various models of structure formation, it was essential to increase both the areal sky coverage and the range of angular scales probed by Python's observations. The Viper telescope extended studies to arcminute scales and higher frequencies, thus superseding Python.

Viper, a 2.1 metre off-axis telescope, was installed at the South Pole in January 1998 (Peterson et al. 2000; see Figure 3). The optical design included an electrically driven mirror which allowed the beam to be rapidly swept across the sky by several degrees, without significant beam distortion or large variations in telescope emission and ground emission pick-up. This large sweep ability allowed Viper to be used to make observations that extended across several degrees, considerably improving

on the data obtained with Python. Among the instruments deployed on Viper were SPARO (see the sub–mm section, above) and ACBAR, the Arcminute Cosmology Bolometer Array Receiver, a 16 element bolometer array cooled to just 250 mK that was deployed in 2000 (Runyan et al. 2003). ACBAR operates at three frequencies centred on 150, 219 and 279 GHz, extending the spectral range over which the CMBR anisotropy has been measured. As with all the CMBR experiments, multiple frequencies are necessary in order to be able to separate the CMBR signal from foreground sources of contamination, produced mostly by dust, synchrotron and free-free radiation. ACBAR was designed specifically to make higher angular resolution measurements of the CMBR anisotropy, from $l = 200$ to 3000 (Kuo et al. 2003). It also aimed to measure the Sunyaev-Zeldovich Effect (SZE) in galactic clusters. The SZE is produced by hot (several million K) gas in galaxy clusters, which Compton scatters the CMB radiation, modifying its blackbody spectral distribution. Data from ACBAR was also combined with data from the Cosmic Background Imager (CBI) and added to that collected by the Wilkinson Microwave Anisotropy Probe (WMAP) to provide the current best estimates on cosmological parameters such as the Hubble constant, the age of the Universe, and the contributions of ordinary matter, cold dark matter and dark energy to the overall composition of the Universe (Spergel et al. 2003).

DASI, the Degree Angular Scale Interferometer, is a 13 element interferometric array designed to extend the angular coverage of the CMBR to values from $140 < l < 910$ (Leitch et al. 2002; see Figure 3). DASI specifically complemented the Viper telescope, especially the mm and sub–mm capabilities provided by ACBAR. DASI made the first detection of polarisation in the CMBR (Kovac et al. 2002), a result not only making the front cover of the Christmas issue of Nature in 2003, but also the front page of the New York Times. These results provided strong support for the underlying theoretical framework that explained the generation of CMBR anisotropy, and lent great confidence to the values of cosmological parameters derived from anisotropy measurements.

The BOOMERanG (Balloon Observations Of Millimetre Extragalactic Radiation and Geomagnetics; see Figure 9) experiment used a 1.2 m microwave telescope carried to an altitude of 38 km by balloon launched from the US coastal station McMurdo by a US/Italian team. It combined the high sensitivity and broad frequency coverage, pioneered by an earlier generation of balloon-borne experiments, with 10 days of integration time obtained on a long-duration balloon flight. Such long periods are possible because a nearly circular pattern of east-to-west jet-stream winds establishes itself in the Antarctic stratosphere for periods of a few weeks at the end of summer. The circulation is generated by the long-lived high-pressure system over the continent caused by the constant solar heating of the stratosphere in summer. This allows, in principle, the launching and recovery of a balloon from roughly the same geographic location and permits a flight path that is almost entirely over land. Constant temperature due to the permanent day conditions during austral summer also permit the balloon to maintain an essentially constant altitude, as well as minimising any temperature fluctuations in the observing platform. The data retrieved from BOOMERanG (de Bernardis et al. 2000) were inconsistent with the then current cosmological models based on topological defects but were consistent with a subset of cold dark matter models. They provided the best evidence at the time that the geometry of the Universe was indeed flat (i.e. Euclidean). As with the DASI result two years later, these measurements also made the front cover of Nature, in April 2000.

8 The Future

The South Pole is nearing completion of a major upgrade of its infrastructure, with the construction of a new Station to replace the Geodesic Dome installed in the 1970's. Two major new astronomical facilities are under development to exploit this enhanced capability for supporting science, the 10 m South Pole Telescope (SPT; Carlstrom 2003), to be used to measure the SZ–effect towards galaxy clusters in the sub–mm, and IceCube (Halzen 2004), a 1 km^3 collector volume neutrino telescope, capable of imaging the high energy neutrino sky for the first time.

The Dome C site at the French/Italian Concordia Station, due to open for wintertime operation in 2005 (Candidi & Ferrari 2003), is currently being evaluated for its astronomy potential. The AASTINO (Lawrence et al. 2003; see Figure 10) operated there autonomously through most of the

winter of 2003, over 1 200 km from the nearest human, with communication made possible through the Iridium satellite system. Dome C is one of the summits of the Antarctic Plateau at an elevation of 3 268 m, and therefore the katabatic winds, which are a constant feature at the South Pole (and at all coastal locations), are minimal. In addition to the colder and drier conditions than at the Pole, the atmospheric turbulence is expected to be considerably smaller, thus leading to new opportunities for adaptive optics correction of wavefronts, and for interferometry (Lawrence 2004).

The summit of the Plateau, the 4 200 m Dome A, is expected to provide even better conditions for astronomy (Burton et al. 1994; Storey et al. 2004), the best on the Earth for a wide range of ground-based astronomy. There are no immediate plans by any nation to construct a base there, and indeed no human has yet visited the site. Nevertheless, plans have recently been advanced to establish an automated facility there, such as the AASTINO.

9 Conclusion

This review of astrophysics at the bottom of the world has encompassed almost a century of human endeavour, beginning with the discovery of the Adelie Land Meteorite in 1912, during the 'heroic' age of Antarctic exploration, a period when humans first began to appreciate the vastness and remoteness of the last continent. It was to be nearly fifty years before the next advances in astronomy were made there, and it is little more than two decades since Antarctic astrophysics began in earnest. The 1990's have seen an avalanche of activities, spanning the continent and in particular focussing on the high inland plateau, where the conditions are particularly appealing for a wide range of astronomical observations. This review has paid particular attention to the development of "photon" astronomy in Antarctica, but equally ambitious have been some of the developments in high energy astrophysics, seeking to measure the incident particle fluxes from space. The scope of this article does not allow for a description of all the projects that have taken place, and a selection of which to portray has had to be made by the authors. A comprehensive compilation of astronomical experiments that have been conducted in Antarctica is, however, given in Table 1. This provides some further detail on experiments described here, as well as information on a number of experiments not mentioned in the text.

Antarctica has already produced a range of stunning astronomical results despite the relative infancy of most of the facilities that have been operating. This is particularly so for the cosmic microwave background experiments, where the stable conditions have facilitated producing results that compare very favourably to those later obtained by satellites, as well as extending the range over which the anisotropies can be probed. There is no doubt that the summits of the plateau provide superlative conditions for the conduct of a wide range of observational astronomy. It will be a fascinating story to follow the development of new facilities on the high plateau in the third millennium, and to wonder about the scientific problems they will be able to tackle.

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10 Tables and Figures

Figure 1: The Adelie Land Meteorite, the first astrophysical find made in Antarctica. It was discovered on a sledging party in Douglas Mawson's Australasian Antarctic Expedition. The Western Sledging Party, led by Frank Bickerton, found the meteorite on 5 December 1912, half buried in the snow, about 18 miles from their base. Photograph Michael Burton, October 2002, with acknowledgment to the Australian Museum, Sydney.

Figure 2: The air tractor used in the 1911–14 Australasian Antarctic Expedition, designed for towing of equipment on sleds, with its engineer Frank Bickerton, discover of the Adelie Land Meteorite. The air tractor only functioned for a few hours, however, on Bickerton's Western Sledging Party, before its pistons seized up. Picture credit: Mitchell Library, State Library of New South Wales, ref. ON 144/H475.

Figure 3: The Martin A Pomerantz Observatory (MAPO). The 60 cm SPIREX infrared telescope was originally hosted on the tower on the the left. In 2000 the DASI CMBR telescope was installed in its place. To the right is the Viper telescope, a 2.1 m off-axis telescope which hosted the ACBAR and SPARO instruments, used for CMBR studies and for mapping polarisation at sub-mm wavelengths, respectively. Image provided by the Office of Polar Programs, National Science Foundation.

Figure 4: The Automated Astrophysical Site Testing Observatory (AASTO), installed at the South Pole in 1997. This self-powered, autonomous laboratory, hosted a suite of site testing instruments for the purpose of quantifying the performance of the site for astronomical use. Image provided by Michael Burton, January 1999.

Figure 5: Schematic diagram of AMANDA, the Antarctic Muon and Neutrino Detector Array, at the South Pole. AMANDA contains 677 widely spaced optical modules, connected together by strings and placed into water-filled holes that were drilled into the ice, before the water re-freezed. Their depths range from several hundred metres to 3 km deep. Image from the AMANDA consortium, courtesy of Christian Spiering.

Figure 6: The SPOT telescope, a 2 inch telescope which was the first optical telescope to be operated through the winter at the South Pole. It is shown as it is currently installed, at the Sunspot Solar Observatory, New Mexico, USA. Photograph Balthasar Indermuehle, November 2002.

Figure 7: SPIREX, a 60 cm infrared telescope, which operated at the South Pole and was sensitive to radiation from 1–5 μm. It was installed just in time to witness the collision of Comet Shoemaker-Levy 9 with Jupiter in July 1994, the only telescope in the world with the opportunity to continuously observe the week-long series of impacts. SPIREX was decommissioned in 2000. Image provided by Michael Burton, January 1999.

Figure 8: Rich Chamberlin in front of the 1.7 m diameter AST/RO dish. The main mirror focuses sub–mm wavelength radio waves and directs them, by a series of mirrors, into a warm room below the telescope. AST/RO has been the most scientifically productive telescope in Antarctica, with over 50 refereed publications resulting from its operation. Photograph copyright Smithsonian Astrophysical Observatory.

Figure 9: The BOOMERanG (Balloon Observations Of Millimetre Extragalactic Radiation and Geomagnetics) experiment, being launched from the US coastal station McMurdo in December 1998. BOOMERanG carried a 1.2 m microwave telescope to an altitude of 38 km by a balloon, and was the work of a US/Italian team. Image provided by Office of Polar Programs, National Science Foundation, 1998.

Figure 10: The AASTINO (Antarctic Astrophysical Site Testing International Observatory), the successor to the AASTO. The AASTINO autonomously operated at Dome C through most of the winter of 2003, with the nearest human over 1,200 km away. Contact was maintained with its operators at the University of New South Wales in Sydney through the Iridium satellite system. On top of the AASTINO are Jon Lawrence, John Storey and Tony Travouillon, who installed the facility in January 2003. Image provided by John Storey, January 2003.